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Mobile Wall-Climbing Robot for NDT inspection of vertical concrete structures

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Abstract
Concrete structures, such as bridges or viaducts, play an important role in global road infrastructure. These types of structures are relatively expensive to build and they are susceptible to outer external influences, which in time deteriorate and lead to the reduction of their structural resistance. To reduce this effect, regular inspection is needed, which is often done manually by using specialized equipment to reach certain parts of bridges and viaducts. This process is both expensive and dangerous for the inspectors to conduct. Within the research project ASAP (Autonomous System for Assessment and Prediction of Infrastructure Integrity) in order to overcome these challenges, we have developed a prototype of a wall-climbing robot (WCR) for nondestructive testing (NDT). In this paper, different iterations of the developed WCR prototypes are presented. In four consecutive prototype designs, we have evaluated and upgraded the adhesion and locomotion system. Finally, a fifth prototype that carries the NDT equipment is presented. The final version of the WCR is equipped with robust and flexible adhesion that enables the robot to adhere to different types of surfaces. We have also addressed the challenges of integrating NDT equipment into the robot. To successfully conduct an inspection, besides the WCR, a safety system, control, and power systems are needed, which are further presented and discussed.

Keywords: Wall-climbing robot, Mobile robot, Inspection robot, Noncontact adhesion, Non-destructive evaluation, Concrete

1 Introduction

Concrete structures like bridges play an essential role in today's modern environment, it would be unimaginable to transport goods and people without them. It is known that the development process for concrete structures is slow and expensive, so it is of great importance to maintain them properly to extend their usability as much as possible. Besides imposed loads from usage, bridges are damaged by environmental factors like chloride-induced corrosion, so appropriate maintenance must be carried out to discover any kind of possible deficiency and thus prevent further deterioration and possible catastrophic failures.

Today, condition assessment of bridges is still done manually. The person in charge of inspection uses visual inspection, semi-destructive and non-destructive techniques. The challenge is that manual inspection has many drawbacks such as being subjective, and it depends on the expertise of the inspector. Furthermore, parts of the bridges that need to be inspected can be unapproachable, so special equipment like gondolas and scaffolds need to be used, which are expensive and most importantly dangerous for the inspector.

1.1 *Non-destructive techniques and ground-penetrating radar*

Compared to visual inspection, the advantage of non-destructive techniques (NDT) is that they can detect deterioration at an early stage, which can result in lower maintenance and repair costs. There are many types of NDT measuring equipment for concrete assessment in use today, and some of them are: Ground penetrating radar (GPR), cover meter, Half-cell potential (HCP) electrode, Electrical resistivity (ER) Wenner's device, Impact echo (IE) hammer, etc. [1]
Of all the methods, GPR is the most widely used today. It has a high inspection speed, which makes it suitable for inspection of large concrete structures, ability to acquire different information simultaneously, simple to use, etc. The operating principle of GPRs (Figure 1) is that it "emits electromagnetic waves into the material and detects the reflected waves from the object. Moreover, the analysis of the reflection strength can be used to locate deteriorated areas."[1].

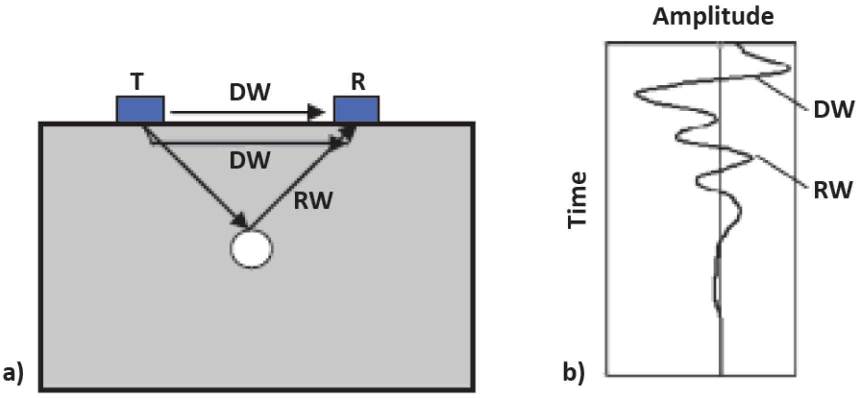

Figure 1: Ground-Penetrating radar working principle**[2]**

To maximize GPR efficiency, it should measure according to a predefined grid with the required dimension in the vertical and horizontal directions. In this paper, we present a prototype of a wall-climbing robot (WCR) that can be equipped with a standard GPR for autonomous inspection. The development of the wall-climbing robot is part of the ASAP project: Autonomous Systems for Assessment and Prediction of infrastructure integrity [3], which consists of a wall-climbing robot, unmanned aerial vehicle, automatic storage of measured data, linking experimental parameters with numerical models, etc.

1.2 *Wall climbing robot introduction*

WCR is a robot capable of adhering to vertical structures using an adhesion system. There are many different types of adhesion systems, and they are usually task-specific, meaning developed robots can only adhere to one type of surface. Adhesion systems can be divided into mechanical adhesion [4], magnetic adhesion which can be further divided into permanent magnets [5], and electromagnetic [6]. Adhesion can be based on molecular forces [7] and electrostatic adhesion [8]. One of the most researched types of adhesion is based on air pressure, and there are many subtypes, like pressure chambers [9], systems that use thrust [10], vortex [11], Bernoulli's principle [12], and mechanism with active [13] and passive [14] vacuum cups. Adhesion systems are task-specific and to mitigate this problem, hybrid adhesion systems started to appear [15]. A hybrid adhesion system combines two or more different types of adhesion systems, resulting in greater flexibility and improved robustness of robot adherence to the surface. WCRs are also classified with respect to active and passive locomotion. Passive locomotion is further divided into ropes, cables, or rail devices for movement [16], whereas active locomotion consists of wheels [17], sliding frames [18], tracked [19], walking [20], or hybrid [21].

For the ASAP project, we have chosen a manual GPR that will be fitted to the robot (GSSI StructureScan Mini Palm XT) due to its compact dimensions and lower weight compared to others. As previously mentioned, the GPR should move on a grid scan in order to determine the condition of reinforcement, with vertical and horizontal lines spaced at predefined intervals of 10-30 cm. The grid scan must be previously planned and then executed by the robotic system. The robots should be capable of accurately and autonomously tracking predefined grid lines. Furthermore, the robot should have a minimum scanning range of 10 m^2, a vertical range of approximately 30 m, and a scanning rate of 0.25 m/s, while the robot's operating time should be minimally 30 minutes.

The main goal of our WCR is to solve two main challenges: a) provide a robust and flexible adhesion system that enables the robot to adhere to the surface, no matter its condition, and b) enable precise multidirectional and continuous robot movement along vertical surfaces. The problem with concrete structures that the WCR should move on is that their surface can diverge greatly depending on the structure condition, thus the adhesion system should be robust and flexible enough to cover all possible surface conditions. We have chosen a hybrid adhesion system, which consists of an Electric Ducted Fan (EDF) with a shroud[22] and a drone-type propulsion unit. The EDF with a shroud produces adhesion force that is a combination of thrust and negative pressure, while the drone-type propulsion units produce thrust forces. By combining these forces in the horizontal and vertical directions the WCR has a flexible and robust adhesion system that does not depend only on surface conditions and the coefficient of friction between the robot and the surface it is adhering to.

Given the locomotion system, the robot must have continuous and precise movements, while not depending on the prior infrastructure preparation (e.g., track and cable locomotion). For enabling omnidirectional locomotion, we have developed a locomotion system with independently active wheels capable of independent rotation (swerve drive kinematics). This enables the robot to have smooth omnidirectional movement, which should result in a shorter inspection time.

2 Robot prototypes

First, based on the chosen type of the adhesion system, different experiments were conducted, and robot prototypes were built. In experiments, different combinations of propellers for the drone-type propulsion unit were tested and their adhesion force to power consumption was compared. Besides propellers, different combinations of shroud geometry and ground clearance for the EDF were tested, where their generated adhesion force to power consumption was compared. A detailed explanation of conducted experiments is published in our previous paper [23].

2.1 Robot Prototypes 1, 2 and 3

Each prototype (Figure 2) served as a base for testing and validating different parts of the adhesion system. Prototype 1 consists of one 80 mm EDF unit, with different types of shroud geometries and shroud ground clearance. It consists of a housing made from aluminum sheet, differential drive wheel locomotion and it is powered by a 24V 6S LiPo battery pack. The robot's dimensions are 335 x 305 mm, and it weighs 2.5 kg. The robot is controlled using an

RC controller in combination with the receiver and Atmega2560 microcontroller. Each wheel has a force sensor for measuring generated adhesion force from the EDF adhesion system. Prototype 1 was discarded in a favour of Prototype 2, as it has had problems with the rigidity of the housing, which affected adhesion system performance, due to a change in shroud ground clearance.

Prototype 2 consists of two 70 mm EDF units with 155 mm shroud and 7.5 mm ground clearance. Besides EDF units, it has a drone-type propulsion unit which consists of two pairs of coaxial BLDC motors with 5" propellers in a pull-push configuration. A combination of an EDF and drone-type propulsion unit gave a robot a hybrid adhesion system, where it can divide adhesion force to the horizontal or vertical as needed. A detailed explanation of prototype 2 can be seen at the [23]. Prototype 2 was discarded in favor of Prototype 4. Even though it has had a hybrid adhesion system, drone-type propulsion units were poorly integrated into the robot, and it affected the EDF adhesion system negatively.

Prototype 3 was never finished as a fully functional robot, as it only served for testing different approaches to the adhesion systems. The idea was to produce adhesion force only using one pair of coaxial BLDC motors in pull and push configuration with 16" propellers. The prototype had an active tilting angle using two Actuonix linear actuators. The active tilting angle helped the adhesion system to have a different distribution of vertical and horizontal adhesion force. It was powered using a 24V, 3kW laboratory power supply and it had a force sensor for measuring the generated force. This prototype was discarded as the produced adhesion force in comparison to the robot size and weight was not satisfactory, as the robot size was one of the key factors.

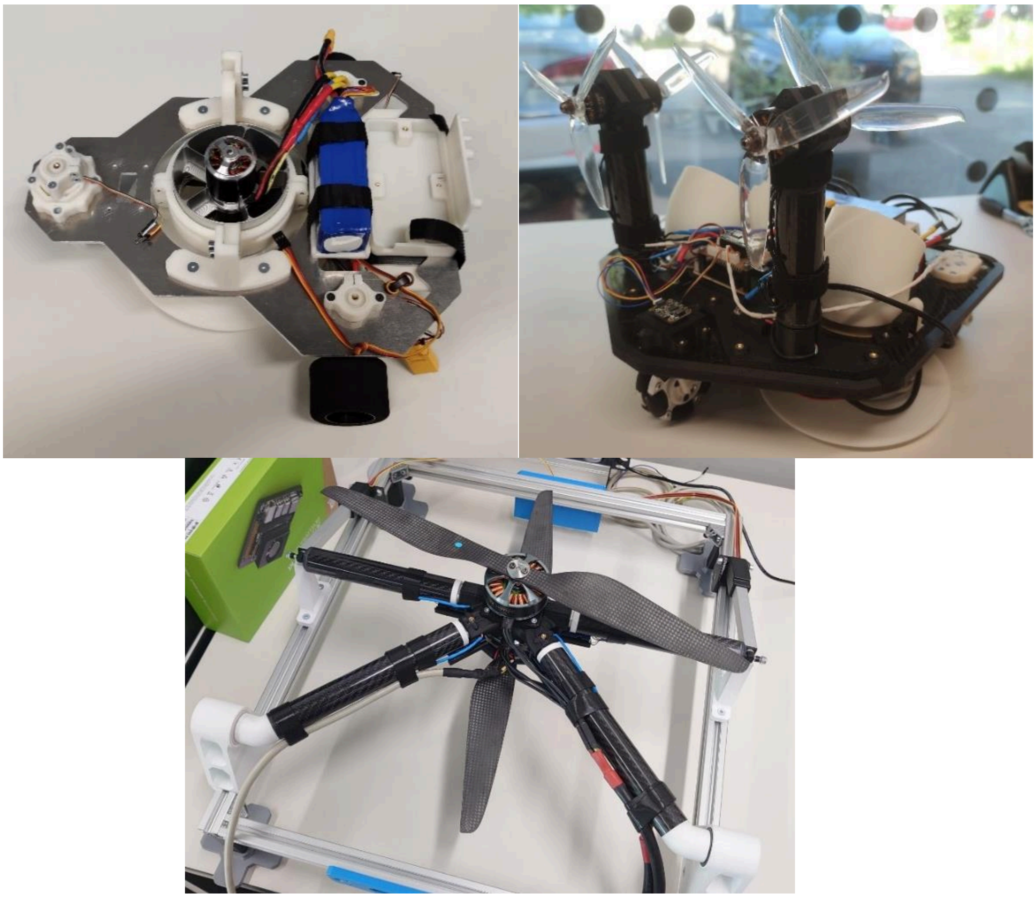

Figure 2: Robot prototypes. Top-Left: Prototype 1; Top-Right: Prototype 2; Bottom: Prototype 3

2.2 *Robot Prototype 4*

The current, fourth, prototype (Figure 3) is based on a hybrid adhesion system and swerve drive kinematics wheeled locomotion system (four independently driven and steerable wheels) enabling smooth omnidirectional movement. The hybrid adhesion system consists of one 70 mm EDF unit with a 155 mm shroud and 7.5 mm ground clearance from the shroud. Besides EDF, it consists of a drone-type propulsion unit with 2 pairs of BLDC motors (T-Motor F80 Pro) with 6” propellers in a coaxial pull-push setup. Drone-type propulsion unit is placed near the center of gravity (CoG) to improve the adhesion system and robot handling. The robot has a compact design, and its housing is made from a combination of carbon fiber tubes and ASA material made using a 3D printing process. Wheels are actuated using Dynamixel smart servo motors. The robot is powered by a 24V, 3kW laboratory power supply using a tethering power cable. The robot has two force sensors for measuring the achieved adhesion force from the EDF unit. Besides force sensors, it uses IMU (Bosch BNO055) and a motor encoder for a relative localization system. For controlling motors OpenCR based on an STM32 microcontroller is used, and for adhesion system control an NXP iMXRT1062 microcontroller is used. Both microcontrollers are communicating with Rasberry Pi4B single-board computer using a USB communication protocol. Raspberry Pi4B is running Linux and Robot Operating System (ROS) middleware. The robot is controlled using WiFi in ROS Master-Slave configuration or with a Bluetooth-based joystick as a standalone unit. The robot has dimensions of 380 x 300 mm (excluding propellers) and its total mass is 3.25 kg. It has a total load capacity of 1.5 kg.

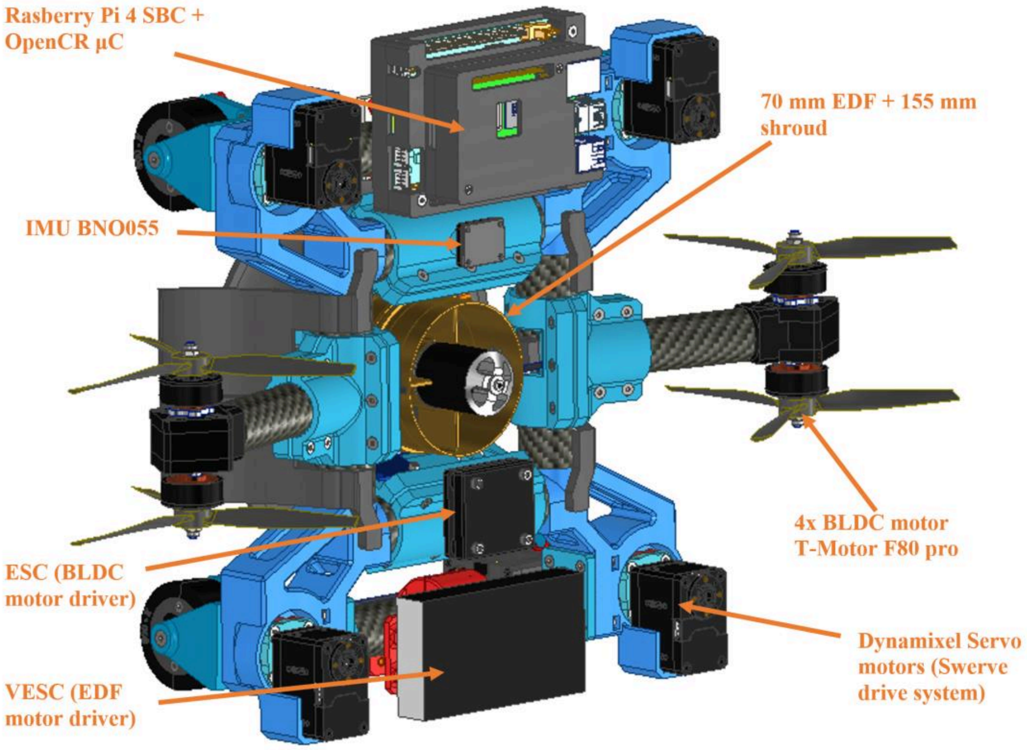

Figure 3: Prototype 4. Top: CAD Model; Bottom: Finished robot

The first experiments of the fourth prototype can be seen in Figure 4. The robot was successfully teleoperated in an open-loop using a Bluetooth joystick and it was successfully driven on the concrete type and smooth type (Plexiglass sheet) surface.

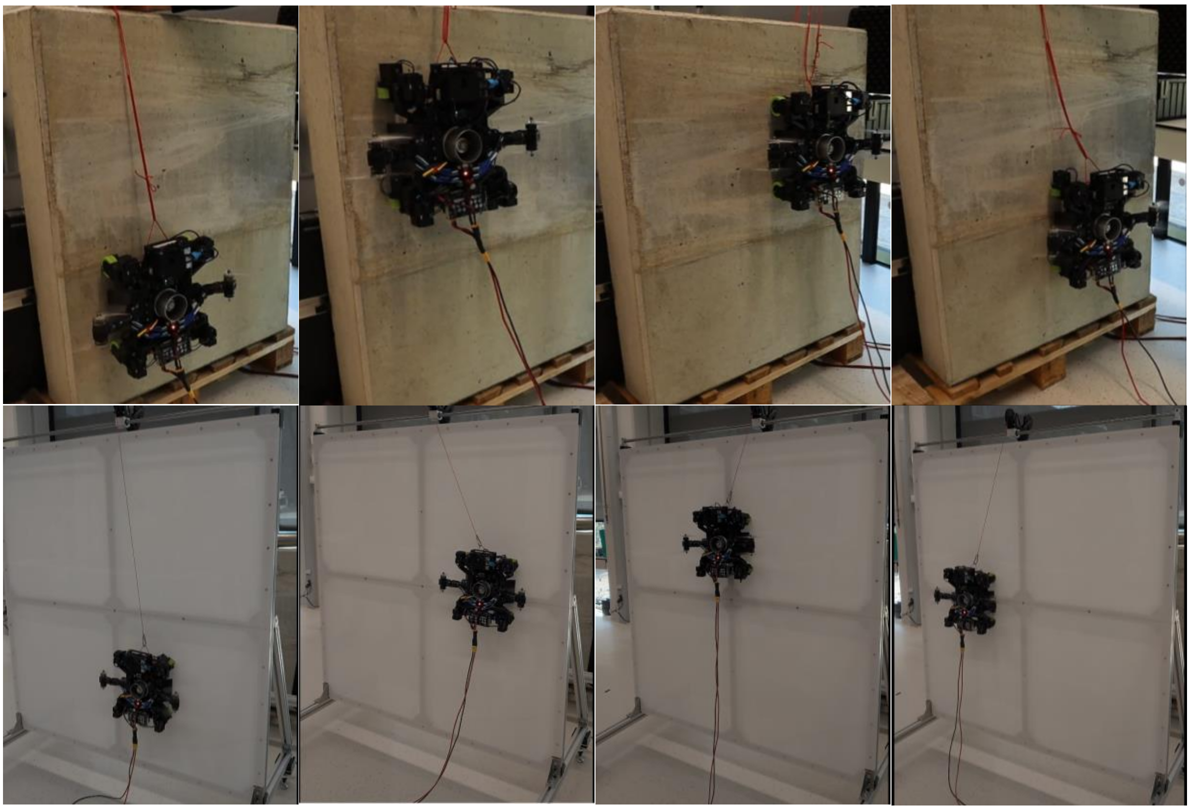

Figure 4: Prototype 4 testing: Top: Movement on a concrete surface; Bottom: Movement on a smooth surface

2.3 *Swerve drive wheeled locomotion*

To test the odometry behavior of the swerve drive kinematics for the 4th robot prototype, two experimental setups were conducted. The robot was given 13 set points that resemble the square shape, and it has had to move to the given setpoints using a local planner and odometry from the motor encoders and swerve drive kinematic model as feedback loop. As a local planer for those measurements, we used $v = v_{max}\tanh(e)$ where v_{max} is the maximum speed of the robot, fixed at 0.15 m/s and e is the distance error between desired and current location of the robot. To compare odometry measurements with the absolute values, we used OptiTrack as an external measuring system. OptiTrack has an accuracy of less than 0.5mm which is more than enough for this type of measurement. Tests were conducted on the horizontal and vertical surfaces as shown in Figure 5.

Figure 6 shows mentioned accumulated error at each corner of the reference square path on the x and y-axis. There are 13 corners for 3 clockwise turns that the robot did. The robot has a maximum error of 49.74 mm (x-axis) and 89.65 mm (y-axis) in the vertical plane and 90.08 mm (x-axis), 77.12 mm (y-axis) in the horizontal plane. In the case of the vertical plane, the error tends to get smaller. This happened because robot orientation changes due to robot slippage that occurs during the lateral movement of the robot, which can be easily spotted in Figure 5.

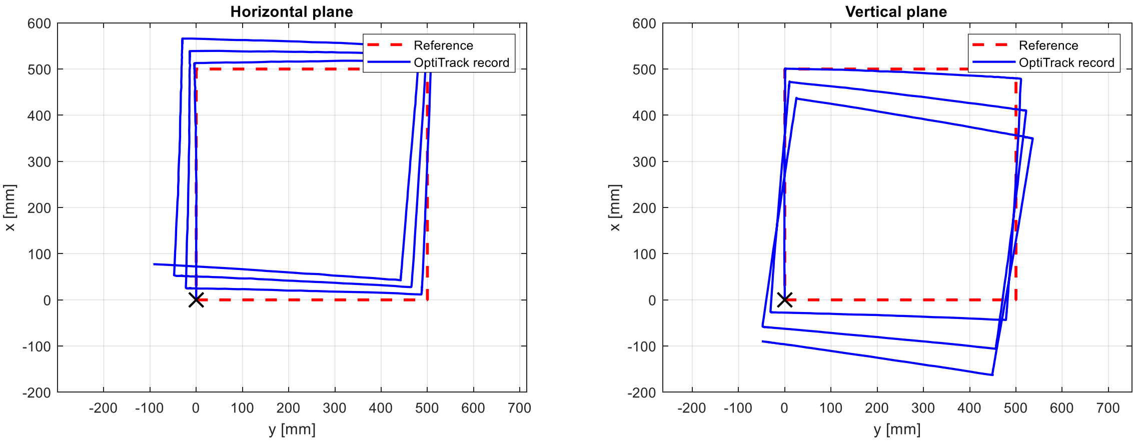

Figure 5: Prototype 4 Swerve drive testing: Left: Robot movement on the horizontal plane; Right: Robot movement on the vertical plane

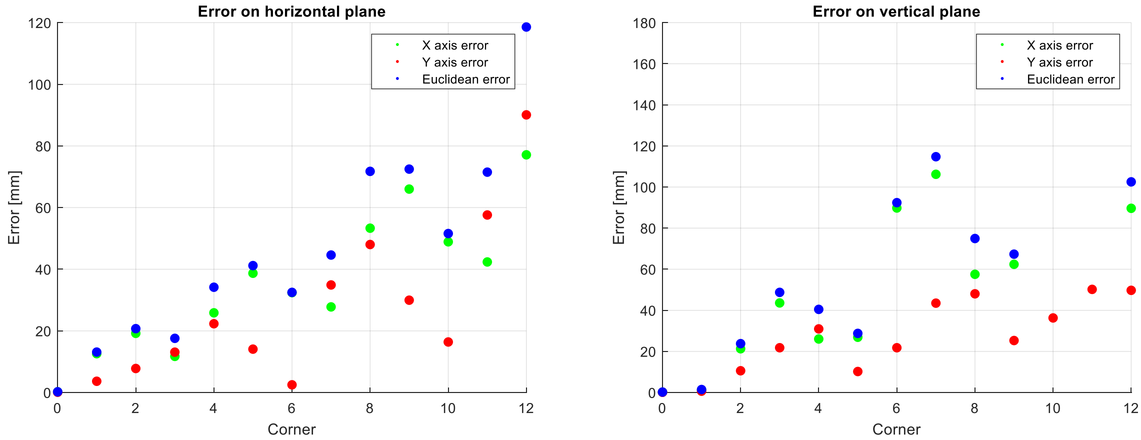

Figure 6: Prototype 4 odometry error at each corner of square path reference: Left: Horizontal plane; Right: Vertical plane

From both Figure 5 and Figure 6, it can be seen that the robot has an odometry error accumulation problem on both horizontal and vertical surfaces. While vertical is more pronounced due to robot slippage that occurs during the lateral movement of the robot in the x-direction. The plan is to solve this problem partially mechanically (better wheels and motors with less backlash that will be used in the next version of the robot), partially with a local planner that works with adhesion system control, and last with sensor fusion (fusing more sensors, as Optical Flow and IMU sensors) that will be able to detect when slippage occurs.

3 Robot prototype 5

After accumulating experience and knowledge from the first four prototypes, we are currently developing the fifth prototype Figure 7 and Figure 8. The fifth prototype is being fitted with GSSI StructureScan Mini Palm XT GPR. It consists of a hybrid adhesion system and swerve drive locomotion unit, like its ancestor.

The difference in the adhesion system is, that now it only uses a drone-type propulsion unit to achieve adhesion force, but it has an active tilting angle for part of the adhesion system, so the appropriate distribution of horizontal/vertical force can be achieved. EDF adhesion unit was replaced with a drone-type propulsion unit, even though the EDF adhesion unit has had satisfactory achievable adhesion force, it depended too much on shroud ground clearance. Small (millimeter) deviations in-ground clearance resulted in big deviations in achievable adhesion force. These deviations were not frequent and could be substituted with the vertical part of the adhesion system, but there is another problem of accidental absorption of surface residual that could damage impellers of the EDF unit.

The four-wheel swerve drive was replaced with three-wheel swerve drive. This resulted in reduced weight and complexity but had as a consequence reduction of robot stability compared to the four wheels swerve drive.

Another difference from the previous robots is the tethering cable. As mentioned before, one of the project's requirements is a minimum operating time of 30 minutes. To satisfy this requirement, the robot should be equipped with heavy batteries that could withstand heavy load from BLDC motors used in the adhesion system. Heavy batteries would affect robot weight, which would affect adhesion system power consumption and that would lead to a vicious circle of “weight to power consumption to the robot operating time”. To avoid this problem, the robot is fitted with a lightweight tethering cable braided with a kevlar and integrates an optic communication fiber. Tethering cable serves as power cable, communication cable, and safety cable at the same time.

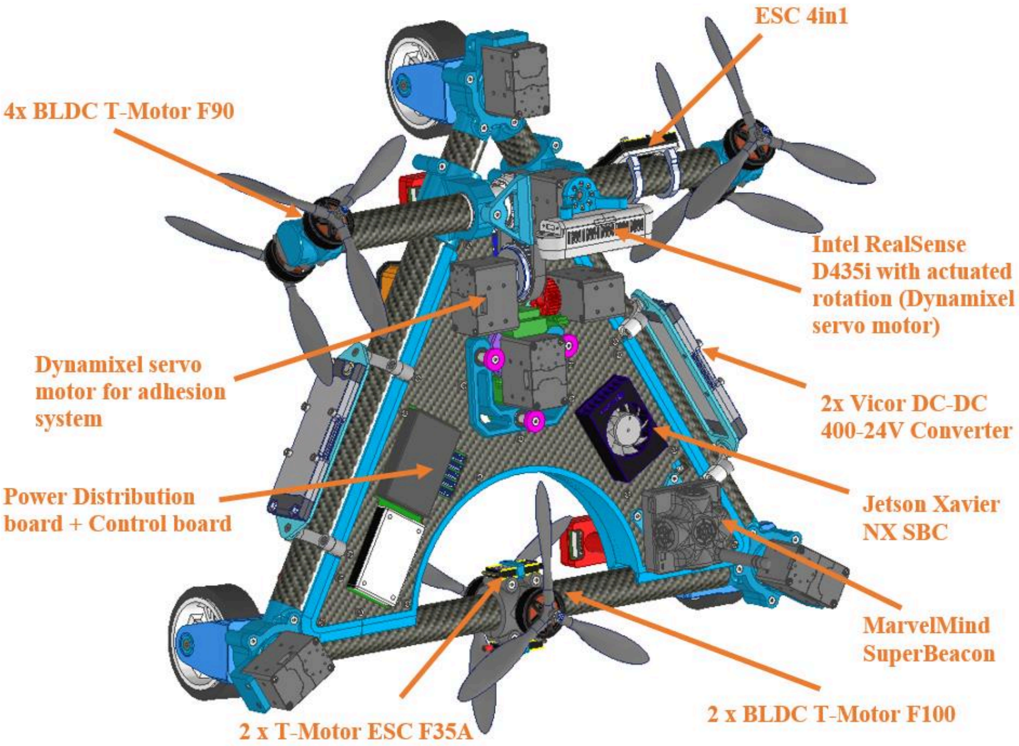

Figure 7: Robot prototype 5 CAD model front

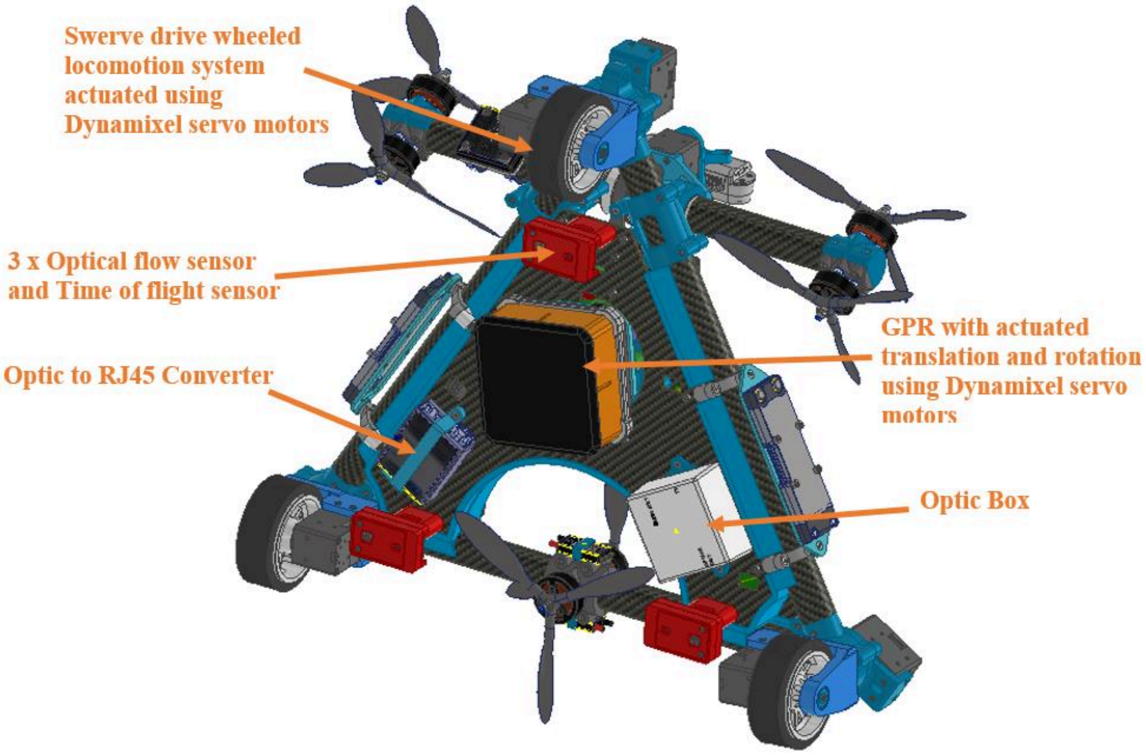

Figure 8: Robot prototype 5 CAD model back

The robot has dimensions of 485 x 425 mm and a weight of 4.25 kg with GPR measuring equipment included.

The robot is divided into eight functional modules:

- Processing and communication module
- Swerve drive locomotion system module
- Actuated adhesion system module
- Vertical adhesion system module
- GPR system module
- Camera system module
- Sensor’s module
- Power module

The Block diagram of the Fifth prototype and components of the modules is shown in Figure 9.

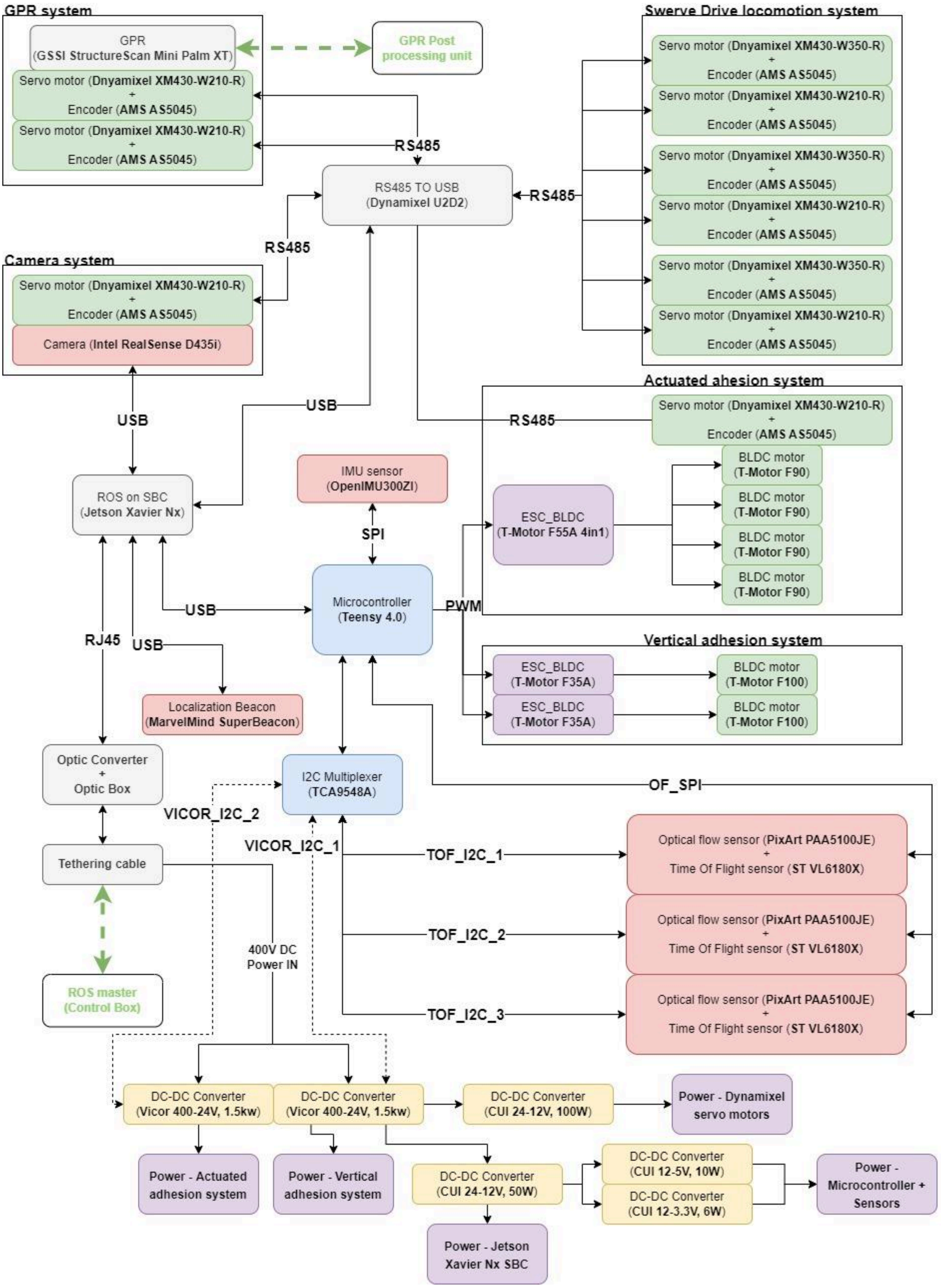

Figure 9: Robot prototype 5 system block diagram

Robot load capacity and power consumption are not yet known at the time of writing this article, as the robot is currently in the production phase, as can be seen in Figure 10.

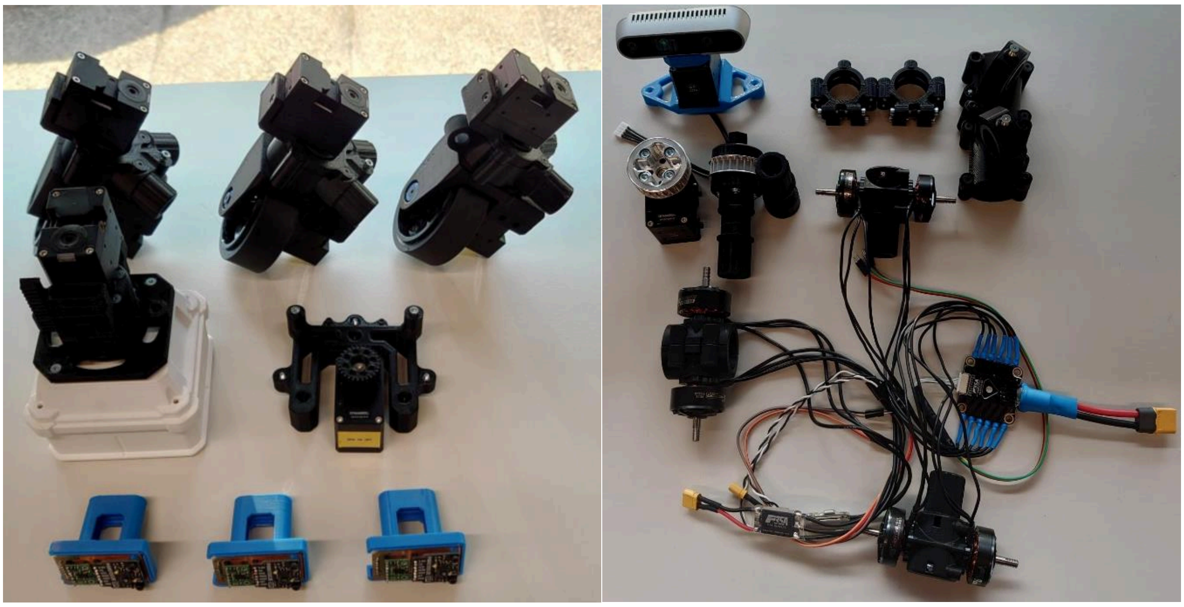

Figure 10: WCR Prototype 5 assembly process

3.1 *WCR inspection system commissioning*

WCR is conceived as a part of the bigger system, which consists of mentioned Wall-climbing robot that does NDT inspection, Safety system modules, and a Ground control station. A simplified block diagram of the whole system is shown in Fig 8.

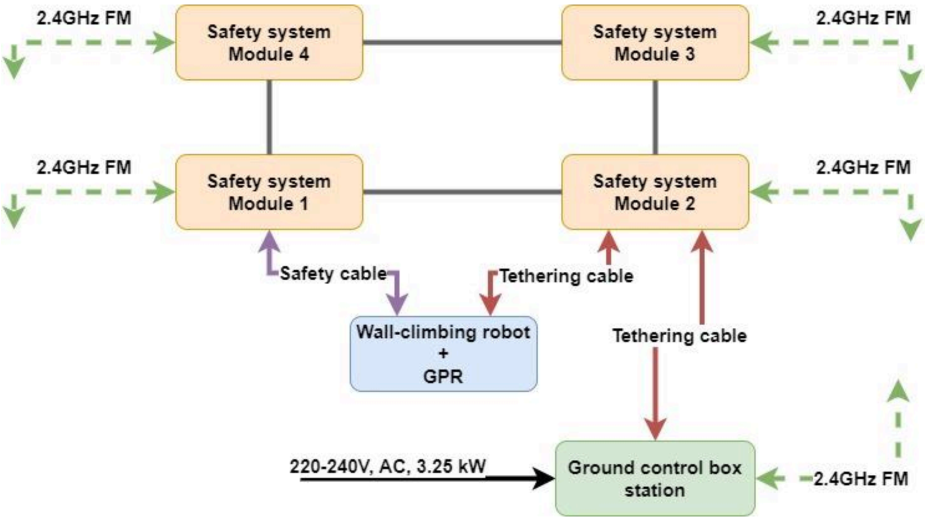

Figure 11: WCR inspection system

Safety system modules are a modular system that consists of a minimum of four modules, and it is being used as a safety system for the WCR. It is working on a principle of holding to the surface using frictional force generated from the tensioning cable between two main modules. Each module has its own battery, control, driving, sensor, and communication system, and the two main modules have a tensioning system. Modules 1 and 2 have additional cable systems that serve as a feeder of a safety cable from one side and tethering from the other side. Each of modules 1 and 2 is fitted with the MarvelMind Beacon as they are part of the WCR absolute localization system.

The ground control box station consists of a power unit for the robot, which converts 220-240V, AC to 400V DC current, which is then transmitted over a tethering cable to the robot. The drum holder for the tethering cable is too situated inside the control box and is extracted/retracted as needed. Control box servers as a holder for the main control computer that connects to the same LAN using RJ45 cable. The control box communicates and sends commands to the Safety modules using the 2.4GHz FM module (nRF24L01).

Commission procedure is the planned to take place in the following order:

- On a bridge pillar picked by the inspector, safety modules are positioned,
- When the safety system is positioned, it tightens the cable to exert enough frictional force that enables it to move in the vertical line,
- A safety rope and tethering cable are positioned on the safety system,
- The safety system moves to the predefined height (e.g. 15 m) and once it reaches the desired height it lowers the safety cable and tethering cable to the ground control box and goes to low power mode
- Safety and tethering cables are interlocked to the WCR and the WCR is positioned to the bridge pillar,
- The ground control box gives power to the WCR and enables it to start the inspection process on the grid line predefined by the inspector,
- Once the WCR starts the movement process, the Ground control box and Safety system are working interchangeably by extracting/retracting the tethering cable and safety rope,
- When the inspection process is over, first WCR lowers itself, then the Safety modules are lowered to the ground.

4 Conclusion

In this paper, the development process of the Wall-Climbing robot is presented. First, the problem of inspecting concrete structures by hand is explained. Then, the solution to the problem is proposed in a term of using the wall-climbing robot. Project and robot requirements are defined, which served as a starting point for robot development. In the series of figures, a prototype development process is presented which led to the development of a fully functional WCR, that is robot prototype 3. All the mentioned prototypes served as a base for the main prototype 5 that is being fitted with the GPR measuring equipment and will be part of the bigger WCR inspection system, whose parts as wall as inspection commissioning process are explained here.

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